Report for 2004WA76B: Three-dimensional Characterization of Riverbed Hydraulic Conductivity and Its Relation to Salmonid Habitat Quality

- Articles in Refereed Scientific Journals:
  - Leek, R., J.Q. Wu, L. Wang, T. Hanrahan, H. Qiu, and M.E. Barber, 2005. Three-dimensional characterization of riverbed hydraulic conductivity and its relation to salmonid habitat quality, Hydrological Processes (In preparation)

Report Follows

PROBLEM AND RESEARCH OBJECTIVES

The health and viability of fish stocks in the Pacific Northwest have long been a critical issue. The recent listing of salmon species as threatened or endangered by the National Marine Fisheries Service signifies the urgent need for fish habitat protection and restoration. Previous studies have overwhelmingly indicated the degradation of natural salmon habitat due to sedimentation from agricultural lands. As a result, many streams and rivers in the Pacific Northwest have been included on the 303(d) list for sedimentation. It is well established that excess sedimentation and its negative impact on the hydraulic properties of the riverbed can directly affect salmon habitat quality. The spatial variability of saturated hydraulic conductivity plays a major role in subsurface water flow and solute transport. The riverbed hydraulic conductivity also has an impact on fish egg survival rate. Yet in most hydrological studies the streambed is represented as a layer of uniform thickness and low permeability.

The main purpose of this study was to characterize the hydraulic properties of the riverbed and their relation to salmonid habitat quality by measuring the three-dimensional riverbed hydraulic conductivity. Field measurements were made within two representative reaches of the Touchet River in the dryland agricultural area of the Pacific Northwest. The specific objectives were: (1) to conduct a detailed field measurement of the three-dimensional distribution of hydraulic conductivity under the riverbed surface using slug tests; and (2) to perform statistical and spatial analyses of the field-measured hydraulic conductivity and the derived specific discharge data as well as their relationship to salmon habitat quality.

METHODOLOGY

Study Site and Sampling Scheme

The study site was located within two adjacent reaches of the Touchet River near Dayton, Washington. Sampling points were placed on a sampling grid with a spatial resolution of 5 m by 3 m by 0.3 m in the longitudinal, transverse, and vertical directions, respectively. The length of each sampled reach was 50 m while the depth reached 1.2 m below the riverbed surface wherever possible. For the chosen reaches, the width of the stream was rather uniform and therefore four measurements were taken across each lateral transect of 9 m. At each depth of a point on the sampling grid, estimates of hydraulic conductivity were made based on three replicates of slug tests as described below.

Measurement of Hydraulic Conductivity

Slug tests were performed by manually driving piezometers into the riverbed. The piezometers were constructed of 15-cm long commercial-grade well-screen connected at the lower end to a 12-cm drive point and welded at the upper end to a galvanized steel pipe (o.d. 4 cm). Individual piezometers were pounded into the riverbed to the desired depth using a solid steel drive rod. A control manifold was then threaded to the top of the piezometers (which remained above the water surface) allowing pressurization and rapid release of the pressure to facilitate the slug test. Once the piezometer was in place, the drive rod was removed, and the pressure transducer and temperature probe was lowered into the piezometer to the bottom plate of the screen section to measure hydraulic head and temperature.

To minimize the interference from any remaining fine sediment (<1 mm), and to establish hydraulic connectivity with the surrounding sediment at each test, the initial water in the piezometer after installation was removed using a hand pump. Additionally, the probe was lifted 8−10cm off the bottom of the piezometer to avoid interference from fine silt. The instrumentation in the probe was connected to the data logger located in a water-tight container on shore by a factory-sealed pressurized cable. The data logger was connected to and actively monitored by a laptop computer. The stream water temperature was also monitored with a thermocouple at the bed surface.

For a partially penetrating piezometer in the riverbed substrate under unconfined flow, the Bouwer and Rice method was adapted to estimate the saturated hydraulic conductivity K

$$K = \frac{r^2 \ln(R_e / R)}{2L_e} \frac{1}{t} \ln\left(\frac{\Delta h_o}{\Delta h_t}\right) \qquad (1)$$

where r is the radius of the well casing, L_e is the length of the well screen, R_e/R is the ratio of the distance from the well, over which the average value of K is measured, to the radius of the gravel envelope, Δh_0 is the drawdown at time $t = 0$, Δh_t is the drawdown at time t.

Determination of Specific Discharge

The measured hydraulic head was then used to estimate vertical hydraulic gradient ($VHG = \Delta h/L$) where L is the depth from the riverbed surface to the measurement position. The vertical hydraulic gradient, in combination with K, determines the specific discharge (v) and therefore the losing or gaining condition at the measured position.

Statistical and Geostatistical Analyses

Descriptive statistics of both hydraulic conductivity K and specific discharge v, including their mean and standard deviation, were estimated. In addition, the normality of K and ln K were tested. Kriging was performed to obtain a three-dimensional geostatistical model of K and ln K.

Estimation of Egg Survival Rate

The values of specific discharge v were used to estimate the expected egg survival at the study site. Survival estimates were based on a predictive model of percent survival as a function of specific discharge. The predictive model relating egg survival with the specific discharge through a riverbed derived from empirical data for sockeye salmon (Cooper, 1965) is given as:

$$S = 167.0 + 46.31 \log (v) \qquad (2)$$

where S is percent survival.

PRINCIPAL FINDINGS AND SIGNIFICANCE

The slug test data from this study yielded a three-dimensional characterization of the riverbed hydraulic conductivity as highly heterogeneous. Such a detailed characterization allows for improved conceptualization and quantification of the dynamic processes at the streambed interface that influence the health of the stream aquatic ecosystem, the hyporheic zone, and the exchange of surface and ground water through this interface.

An example of slug test results is shown in Fig. 1 below. Depth of recovery as a function of time was fitted to the Bouwer and Rice equation to obtain *K*. The rate of recovery is represented by the shape of the curve, and the faster the recovery, the greater the *K* value.

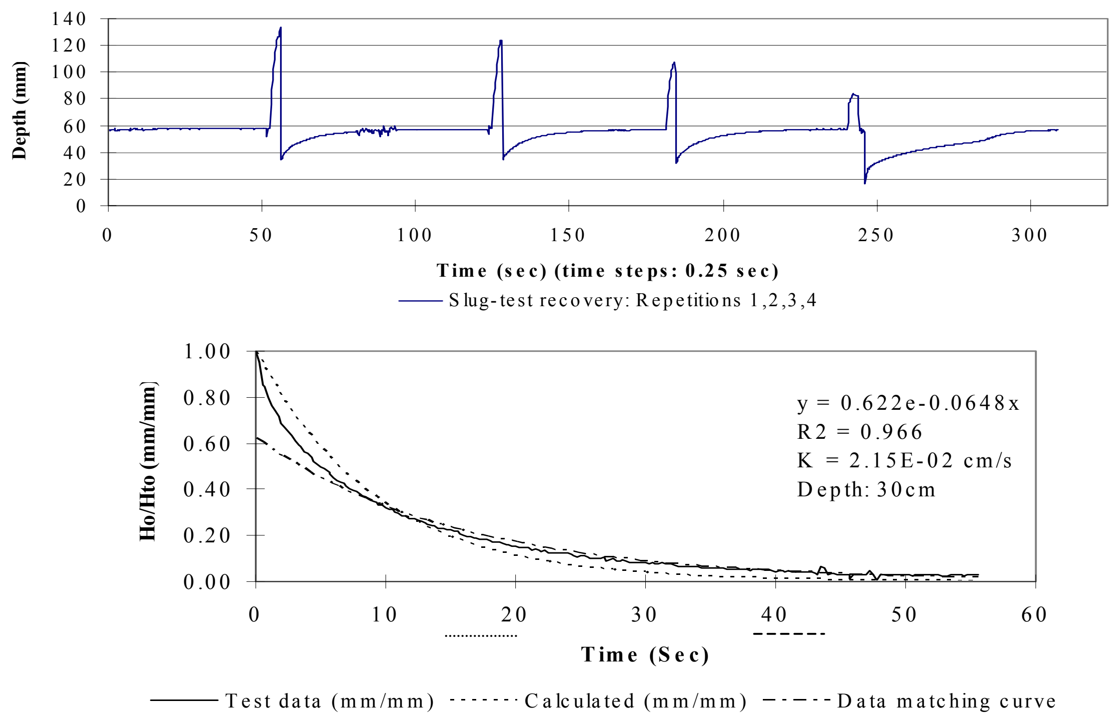

Fig 1**.** Typical slug test recovery curves for one location within the upper reach. In the lower panel, H_o/H_t is a dimensionless value representing head recovery. *K* is determined using the Bouwer-Rice equation through curve-matching.

Table 1 presents the summary statistics of the field-measured hydraulic properties at different depths for the upper reach. Within the riverbed of the upper reach, there exists significant spatial variability of the hydraulic conductivity spanning three orders of magnitude. The direction of flow varies from place to place with both down- and upwelling occurring in random form.

Fig 2 illustrates the spatially varying egg survival rate *S*, specific discharge *v*, vertical hydraulic gradient *VHG*, and hydraulic conductivity *K*, all calculated for the sediment depth of 30 cm in the upper reach. The egg survival statistics indicates that approximately 41% of the riverbed surface area in this upper reach will have habitat gravels, underlain by highly permeable material, which results in a survival rate greater than 55%. Further, 29% of this surface area provided an estimated survival rate greater than 75%. The location at about 35 m corresponds to a highly permeable (*K*) region (*K* = 0.467 cm/s), with negative *VHG* and positive *v*, and thus relatively high egg survival indexes (67 %, 54 % and 76 % across the transect).

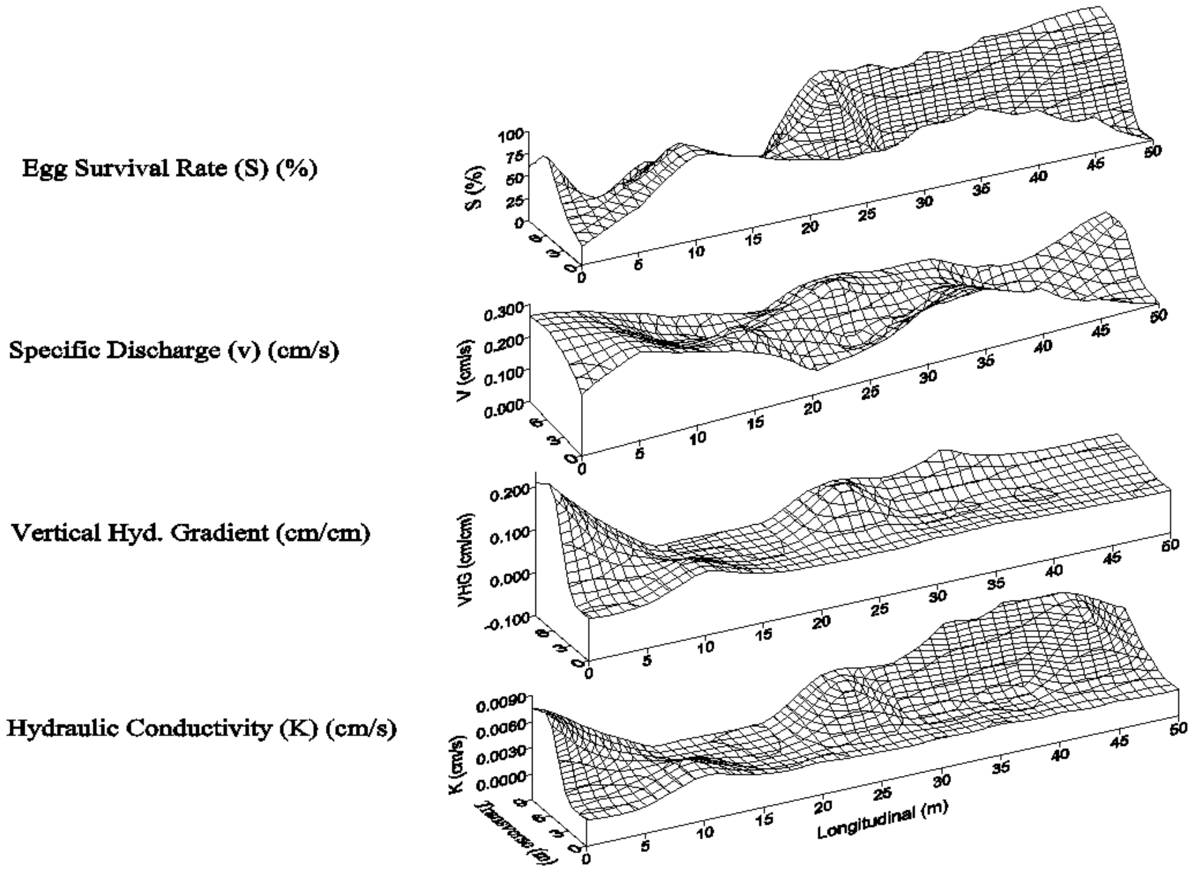

Fig. 2. Two-dimensional krigging of *S*, *v*, *VHG*, and *K* at the 30-cm depth of the upper reach.

In sum, a complete, three-dimensional characterization of riverbed hydraulic conductivity in the Touchet River, a Pacific Northwest stream on basaltic bedrock, was obtained in this project. Such characterization contributes to a better understanding of the natural heterogeneity of the riverbed and surface water and ground water interactions in this region. The study provides additional evidence that the streambed is a dynamic interface far more complex than previously generalized. The secondary product of the study is the preliminary assessment of salmon habitat quality based field measured riverbed hydraulic properties in a dryland reach typically found in the Touchet River watershed in the Lower Columbia River Basin. This study serves as a pilot study for characterizing riverbed heterogeneity using slug tests and relating riverbed hydraulic conductivity to salmon habitat quality. Additionally, it serves as a foundation for future efforts to assess the impact of agricultural management practices on stream water quantity and quality.

Table 1. Descriptive statistics of field-measured *K*, *VHG*, and *v* at different depths within the upper reach.

Descriptive Statistics	*VHG* (cm/cm)	*K* (cm/s)	*v* (cm/s)
30cm			
Minimum	-0.07	1.81E-03	-9.33E-04
Maximum	0.28	8.60E-01	2.43E-01
Mean	0.12	1.48E-01	2.03E-02
Standard Deviation	0.09	2.51E-01	4.44E-02
60cm			
Minimum	-0.03	1.12E-03	-1.52E-03
Maximum	0.25	7.46E-01	8.33E-02
Mean	0.10	7.79E-02	7.82E-03
Standard Deviation	0.07	1.52E-01	1.65E-02
90cm			
Minimum	0.03	1.05E-03	1.16E-04
Maximum	0.23	4.47E-01	4.52E-02
Mean	0.10	8.98E-02	7.90E-03
Standard Deviation	0.06	1.57E-01	1.54E-02
Bottom*			
Minimum	-0.16	1.68E-03	-2.34E-01
Maximum	0.35	1.45E+00	5.17E-02
Mean	0.08	2.28E-01	1.37E-03
Standard Deviation	0.10	3.61E-01	4.68E-02

* None of the piezometers in the upper reach were driven to the full 120-cm depth as in the lower reach. Sediments ranged in depth from less than 30 cm to approximately 110 cm.